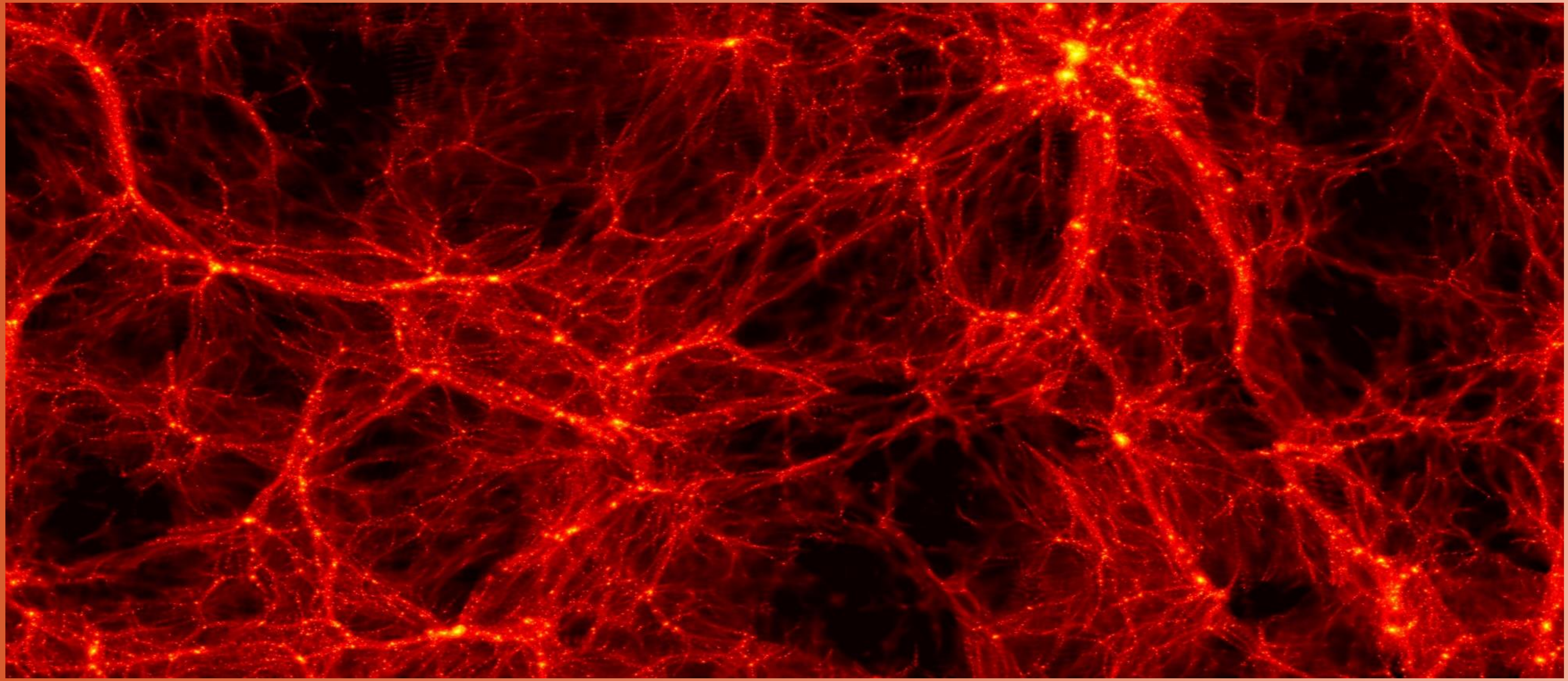
Dark Energy and the running of Λ



Adrià Gómez-Valent

Centro de Ciencias de Benasque Pedro Pascual
September 2015

LAYOUT OF THE TALK

- Basic properties of the cosmological term
- Alternatives to alleviate the existing problems associated to the CC
- Dynamical Λ in QFT in curved space-time
- Background cosmological solutions
- Fitting results
- Linear structure formation
- Conclusions

Some details on the cosmological costant (CC)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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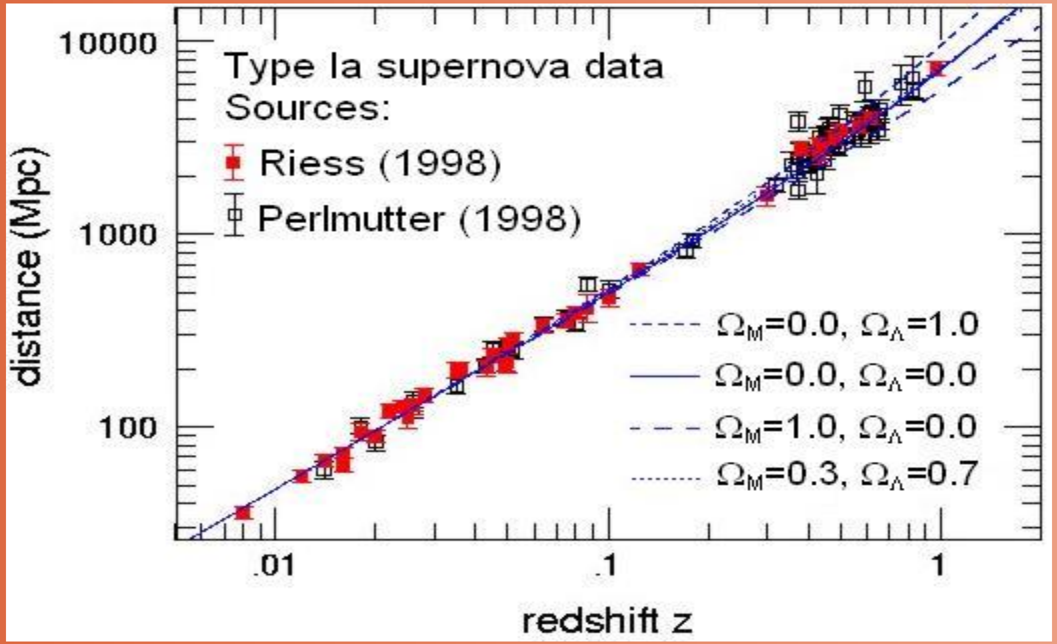
Easy interpretation from the thermodynamical point of view. Universe <-> box expanding adiabatically

$$\Delta U = \rho_\Lambda \Delta V$$

Due to its negative pressure, the CC has repulsive gravitational power!

$$\frac{\ddot{a}}{a} = \frac{4\pi G}{3}(2\rho_\Lambda - 2\rho_r - \rho_m)$$

1998: Accurate measurement of the luminosity-redshift curve of distant SNIa carried out by the Supernova Cosmology Project and the High-z Supernova Search Team .



→Our Universe is speeding up! The so-called concordance ΛCDM model fits well the data. A positive rigid Λ could (in principle) explain the 70% of the energy content of the universe.

$$\rho_\Lambda^{(0)} \sim 10^{-47} GeV^4$$

QFT plays its role

- Several contributions to the effective value of Λ: $\Lambda_{eff} = \Lambda_{vac} + \Lambda_{ind}$

→ Zero-point energy $\rho_{ZP} = \int_0^{k_{max}} \frac{d^3k}{(2\pi)^3} \frac{1}{2}\sqrt{k^2+m^2} \approx \frac{k_{max}^4}{16\pi^2}$

Even if we consider the QCD scale (~0.1 GeV), we obtain a discrepancy of >40 orders of magnitude with respect to the observed value of ρ_Λ, i.e. $\rho_\Lambda^{(0)} \sim 10^{-47} GeV^4$!

→2013: LHC -> Higgs boson → Higgs vacuum energy

$$\rho_{ind}^{(0)} \sim -10^8\, GeV^4$$

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OLD COSMOLOGICAL CONSTANT PROBLEM, FINE TUNING IS NEEDED

MODEL INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION

- Reference: Sahni, V., Shafieloo, A., & Starobinsky, A. A., 2014, ApJL, 793 L40 (arXiv:1406.2209)

- Their Diagnostic:

$$Omh^2(H_i, H_j) = \frac{[H(z_i)/100]^2 - [H(z_j)/100]^2}{(1+z_i)^3 - (1+z_j)^3}$$

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Planck 2015

$$\mathrm{Omh}^2 = \Omega_m h^2 = 0.1415 \pm 0.0019$$

Using the available Hubble function data set

$$\mathrm{Omh}^2 = 0.1250 \pm 0.0039$$

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Probably, Λ must be dynamical

Some attempts to alleviate the existing conundrums

- Scalar field theories: k-essence (quintessence, phantom fields, etc.)

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + P(\phi, X)\right] + S_m \qquad X = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

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- Modified gravity theories: f(R) gravity, relaxing mechanisms, etc.

Dynamical Λ in QFT in curved space-time

- Running Λ. Renormalization Group equation (RGE):

$$\frac{d\rho_\Lambda(\mu)}{d\ln\mu} = \frac{1}{(4\pi)^2}\left[\sum_i B_i M_i^2\,\mu^2 + \sum_i C_i\,\mu^4 + \sum_i \frac{D_i}{M_i^2}\,\mu^6 \;+ \ldots\right]$$

M_i are the masses of the particles contributing in the loops and B, C, D, etc. are dimensionless constants.

The vacuum/dark energy density depends on the energy scale μ that governs the dynamics of the universe, i.e. ($H^2, \dot{H}$).

We exclude the contribution of the odd powers of μ in order to respect the general covariance of the theory.

Dynamical Λ in QFT in curved space-time

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$$\rho_\Lambda(t) = c_0 + \sum_{k=1} \alpha_k H^{2k}(t) + \sum_{k=1} \beta_k \dot{H}^k(t)$$

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Low energy limit

$$\rho_\Lambda(H,\dot{H}) = \frac{3}{8\pi G}\left(C_0 + C_{\dot{H}}\dot{H} + C_H H^2\right)$$

If Λ behaves like vacuum…

$$\frac{d}{dt}\left[G(\rho_m + \rho_\Lambda)\right] + 3\,G\,H\,(\rho_m + p_m) = 0$$

The variation of Λ has deep consequences

I: G is constant and matter exchanges energy with the vacuum.

- Gómez-Valent A., Solà J. & Basilakos S., 2015, J. Cosmol. Astropart. Phys. 0402, 006
- Gómez-Valent A. & Solà J.,2015, Mont. Not. Roy. Astron. Soc. 448, 2810-2821

II: G is time-dependent and matter is covariantly conserved.

- Solà, J., Gómez-Valent, A., & De Cruz Pérez, J., 2015, ApJ, 811, L14

III: I+II

- Extra difficulty: we have more unkown functions than independent equations!

What if Λ is not vacuum?

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General Dark Energy (DE) fluid $p_D = \omega_D \rho_D$ $\frac{d\omega_D}{dt} \neq 0$

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→ DE density function $\rho_D(H)$ → COSMOLOGICAL BACKGROUND SOLUTIONS

↓

Linear structure formation

Models under study

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\begin{aligned}
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Bad defined LCDM limit

Also motivated from other theoretical frameworks

QCD ghost DE models

Entropic-force DE models

Background solutions: DA2 models

Hubble rate

$$E^2(a) = a^{3\beta} + \frac{C_0}{H_0^2(1-\nu)}(1-a^{3\beta}) + \frac{\Omega_m^{(0)}}{1-\nu+\alpha}(a^{-3}-a^{3\beta}) + \frac{\Omega_r^{(0)}}{1-\nu+4\alpha/3}(a^{-4}-a^{3\beta})$$

Energy densities

$$\rho_D(z) = \frac{\rho_c^0 C_0}{H_0^2(1-\nu)} + \rho_c^0\,\Omega_m^0\,\frac{\nu-\alpha}{1-\nu+\alpha}\,(1+z)^3 - \rho_c^0\,\eta\,(1+z)^{-3\beta}$$

$$\rho_m(a) = \rho_m^{(0)} a^{-3}$$

$$\rho_r(a) = \rho_r^{(0)} a^{-4}$$

EoS parameter

$$\omega_D(z) = -\frac{1}{1+\frac{H_0^2(1-\nu)}{C_0}\Omega_m^0\,\frac{\nu-\alpha}{1-\nu+\alpha}\,(1+z)^3}$$

with

$$\beta \equiv (1-\nu)/\alpha$$

$$\eta = \frac{C_0}{H_0^2(1-\nu)} + \frac{\Omega_m^{(0)}}{1-\nu+\alpha} - 1$$

$$C_0 = H_0^2\left[\Omega_D^{(0)} - \nu + \alpha\left(1 + \omega_D^{(0)}\Omega_D^{(0)} + \frac{\Omega_r^{(0)}}{3}\right)\right]$$

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- We recover the LCDM expressions when ν=α=0
- DA1 solutions by doing α=0
- DA3 solutions by doing ν=0
- DC2 solutions by doing C_0=0

with

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Background solutions: DC1 models

Hubble rate

$$E(z) = \frac{\epsilon + \Sigma(z)}{2(1-\nu)}$$

Energy densities

$$\rho_D(z) = \rho_c^0\,\left[\epsilon\, E(z) + \nu\, E^2(z)\right]$$

EoS parameter

$$\omega_D(z) = -1 + \frac{\Omega_m^{(0)}(1+z)^3[\epsilon + 2\nu E(z)]}{E(z)\,[\epsilon + \nu E(z)]\,[2(1-\nu)E(z) - \epsilon]}$$

with

$$\Sigma(z) = \sqrt{\epsilon^2 + 4(1-\nu)[\Omega_r^{(0)}\,(1+z)^4 + \Omega_m^{(0)}(1+z)^3]}$$

Background solutions: DC1 models

Hubble rate

$$E(z) = \frac{\epsilon + \Sigma(z)}{2(1-\nu)}$$

DH solutions obtained by setting v=0

Energy densities

$$\rho_D(z) = \rho_c^0 \left[\epsilon\, E(z) + \nu\, E^2(z)\right]$$

EoS parameter

$$\omega_D(z) = -1 + \frac{\Omega_m^{(0)}(1+z)^3[\epsilon + 2\nu E(z)]}{E(z)\,[\epsilon + \nu E(z)]\,[2(1-\nu)E(z) - \epsilon]}$$

with

$$\Sigma(z) = \sqrt{\epsilon^2 + 4(1-\nu)[\Omega_r^{(0)}\,(1+z)^4 + \Omega_m^{(0)}(1+z)^3]}$$

Best-fit values

Combined Likelihood function:

- DA models: SNIa + CMB R shift parameter + BAO A + BAO d_z+ LinearStructureFormation
- DC models: SNIa + BAO A + LinearStructureFormation

Model	$\Omega_m^{(0)}$	$\overline{\Omega}_m^{(0)}$	$\nu_{\rm eff} = \nu - \alpha$	$\bar{\nu}_{\rm eff}$	σ_8	$\overline{\sigma}_8$	χ^2_r/dof	χ^2/dof	$\overline{\chi}^2/dof$	AIC	$\overline{\rm AIC}$
ΛCDM	$0.291^{+0.008}_{-0.007}$	0.286 ± 0.007	-	-	0.815	0.815	569.21/592	584.91/608	584.38/608	586.91	586.38
$\mathcal{D}$A1	$0.286^{+0.012}_{-0.011}$	0.281 ± 0.005	-0.024 ± 0.018	-0.028 ± 0.016	0.773	0.770	565.50/591	573.02/607	573.31/607	577.02	577.31
$\mathcal{D}$A2	$0.286^{\pm}0.011$	0.281 ± 0.005	-0.024 ± 0.018	-0.028 ± 0.016	0.772	0.769	565.57/591	573.03/607	573.40/607	577.03	577.40
$\mathcal{D}$A3	$0.287^{\pm}0.011$	0.282 ± 0.005	$-0.023^{+0.017}_{-0.018}$	-0.027 ± 0.015	0.777	0.773	565.63/591	573.44/607	573.47/607	577.44	577.47
$\mathcal{D}$C1	0.286 ± 0.014	0.335 ± 0.007	-0.64 ± 0.13	-0.35 ± 0.05	0.440	0.735	563.86/584	880.74/600	635.23/600	884.74	639.23
$\mathcal{D}$H	0.242 ± 0.008	0.286 ± 0.005	-	-	0.513	0.729	639.85/585	809.61/601	677.11/601	811.61	679.11
$\mathcal{D}$C2	0.285 ± 0.013	0.295 ± 0.006	$1.03^{+0.09}_{-0.06}$	1.02 ± 0.01	0.666	0.752	563.53/584	594.13/600	572.17/600	598.13	576.17

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For DA models: $\nu_{eff} = \nu - \alpha$ For DC models: $\nu_{eff} = \nu$

The Akaike information criterion

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In case $N/n_p > 40$

If data is normally distributed

$$\mathrm{AIC} = -2 \ln \mathcal{L}_{\max} + 2 n_p = \chi^2_{\min} + 2 n_p$$

The Akaike information criterion

$$(\Delta \mathrm{AIC})_{ij} = (\mathrm{AIC})_i - (\mathrm{AIC})_j$$

$$\Delta_{ij} \equiv |\Delta(\mathrm{AIC})_{ij}|$$

Rule of thumb:

- $\Delta_{ij} < 2$ no evidence
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$\Delta_{ij} \approx 9$

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- **Strong evidence in favour of DC2 models (in front of LCDM)?**

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NOT THE CASE!

The bad behavior of DC2 model at high z

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$$E^2(a) = a^{3\beta} + \frac{\Omega_m^{(0)}}{1-\nu+\alpha}(a^{-3} - a^{3\beta}) + \frac{\Omega_r^{(0)}}{1-\nu+4\alpha/3}(a^{-4} - a^{3\beta})$$

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High-z regime

$$E^2(a) = \frac{\Omega_r^{(0)} z^4}{1-\nu+4\alpha/3}$$

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$$E^2(a) = \frac{3}{4}\Omega_r^{(0)} z^4$$

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UNACCEPTABLE: DC2 model totally EXCLUDED

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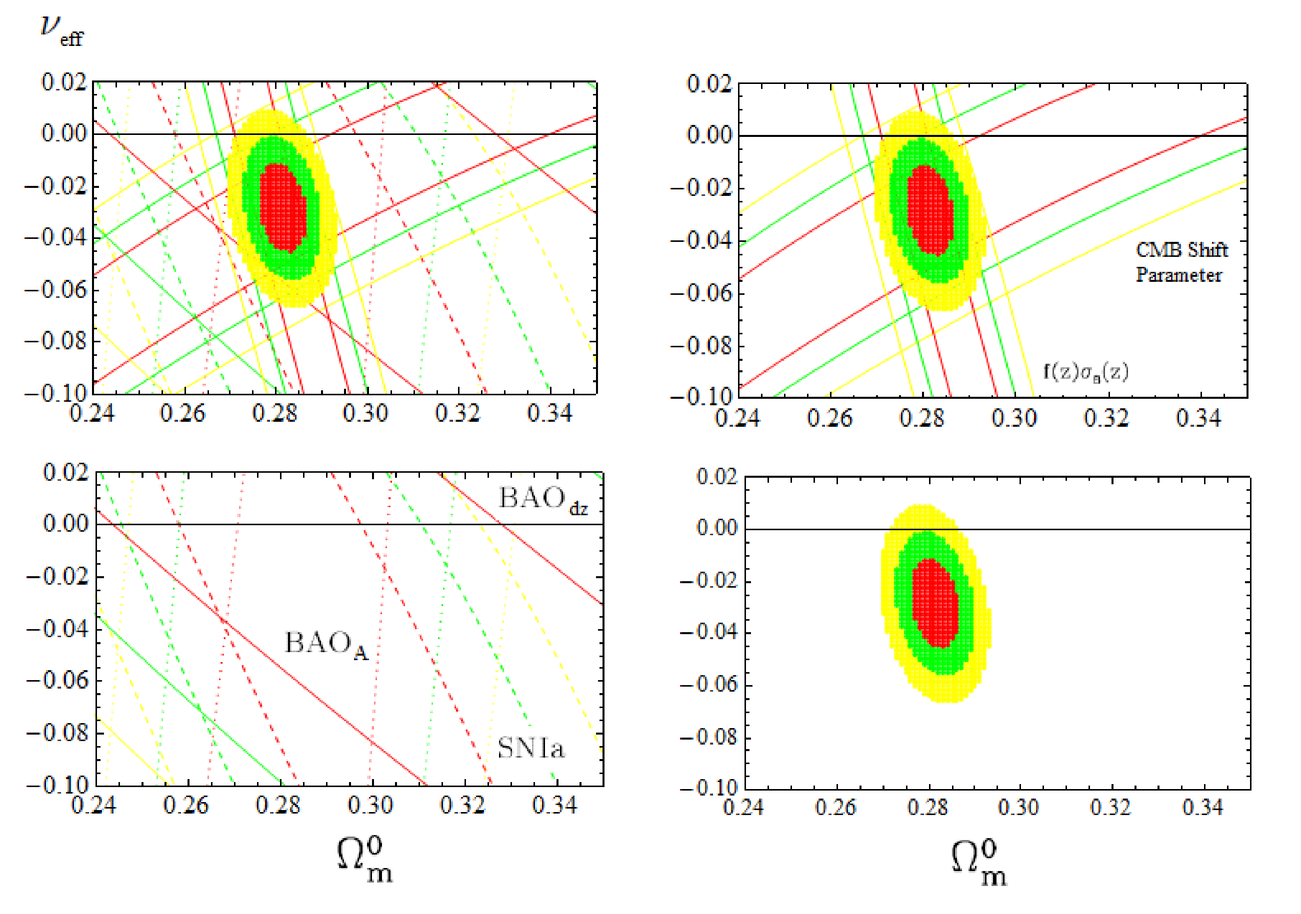
Contour Lines of DA models



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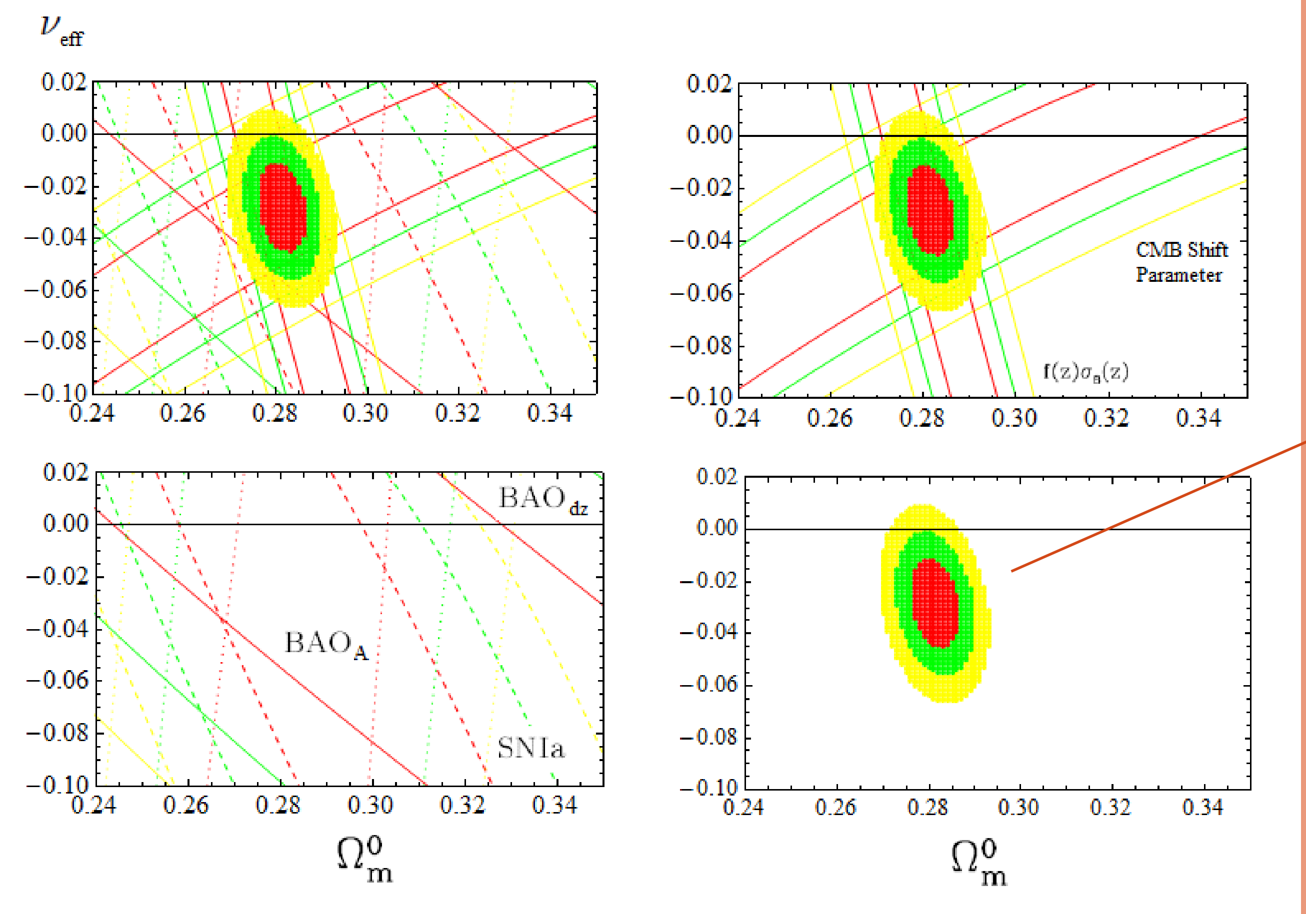
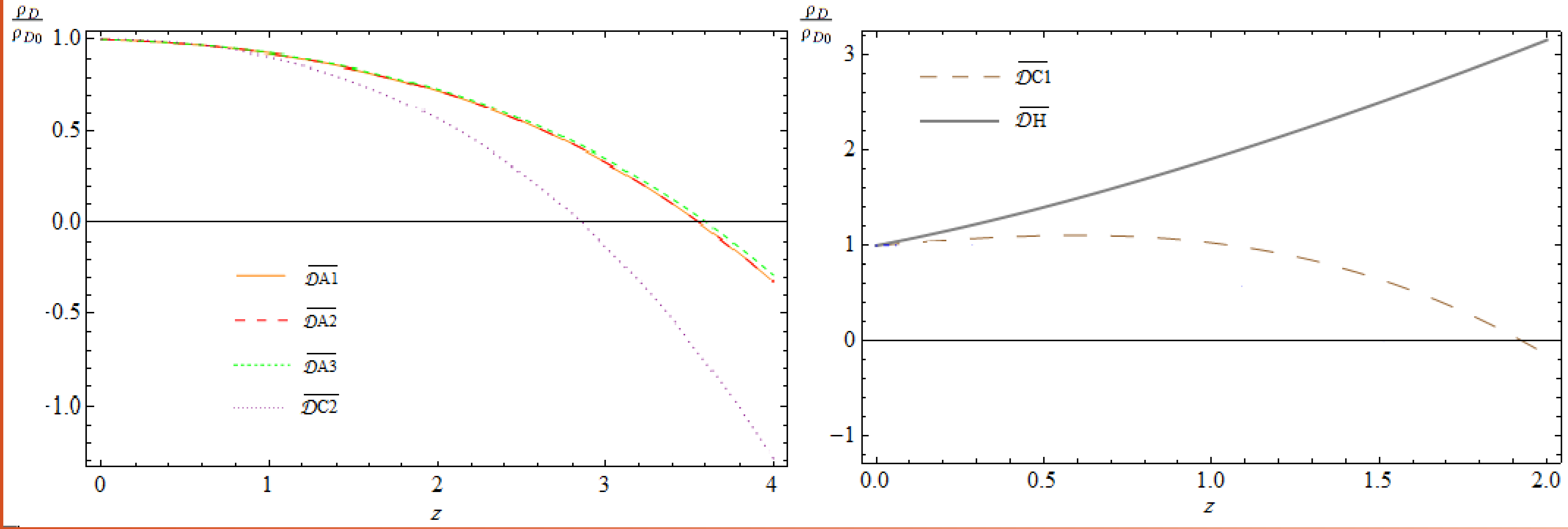


The $\nu_{eff} = 0$ (ΛCDM) region is disfavored at $\sim 3\sigma$ level

Dark Energy density for the various models



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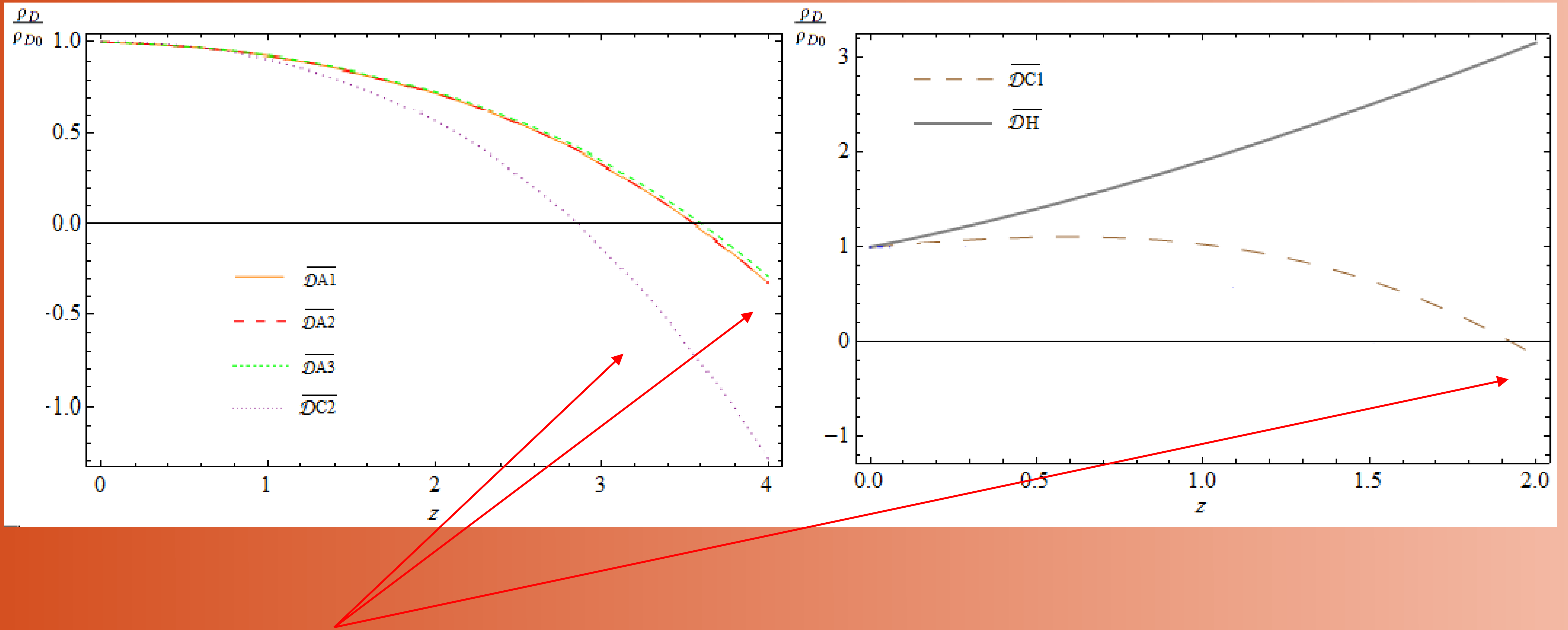
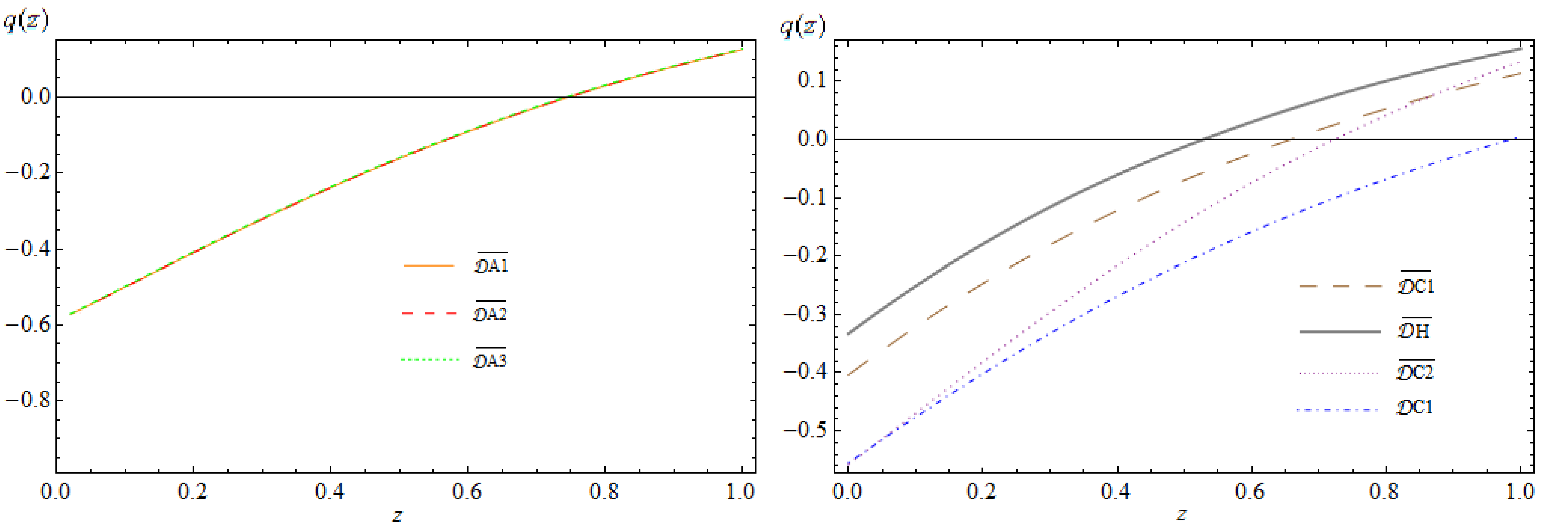


Notice that in the past DE slows down the expansion of the Universe!

Acceleration parameter

$$q = -\frac{\ddot{a}a}{\dot{a}^2}$$



ΛCDM: $z_{tr} \approx 0.71$

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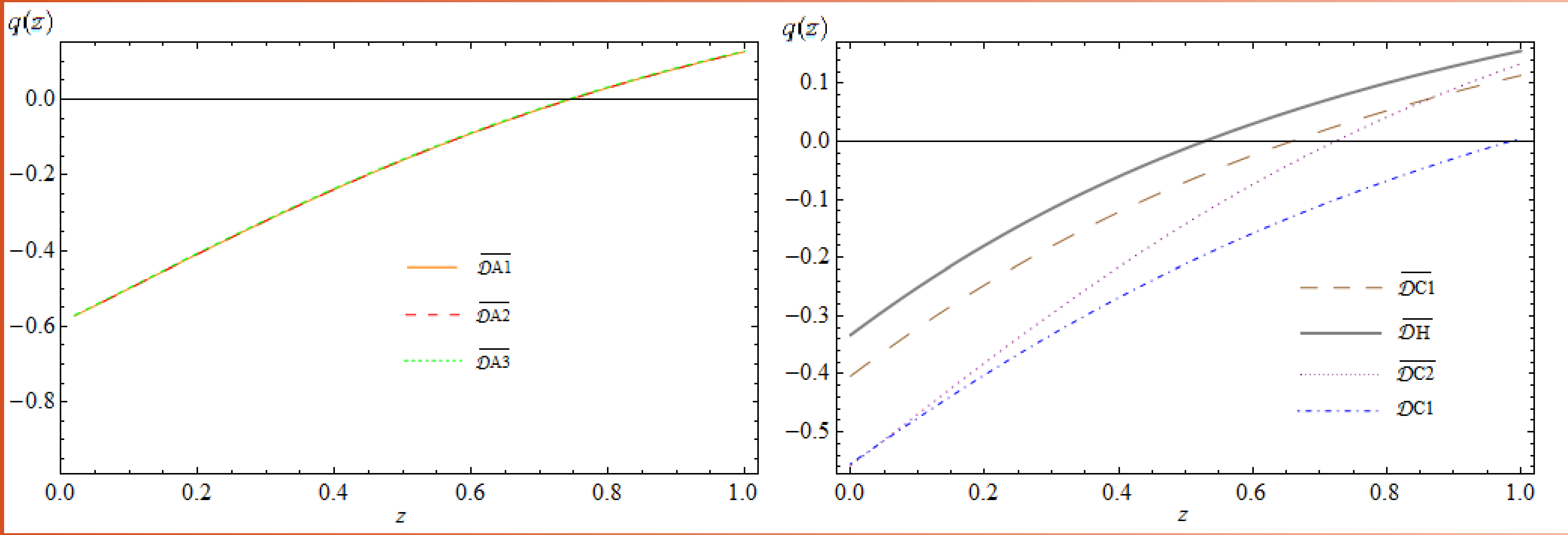

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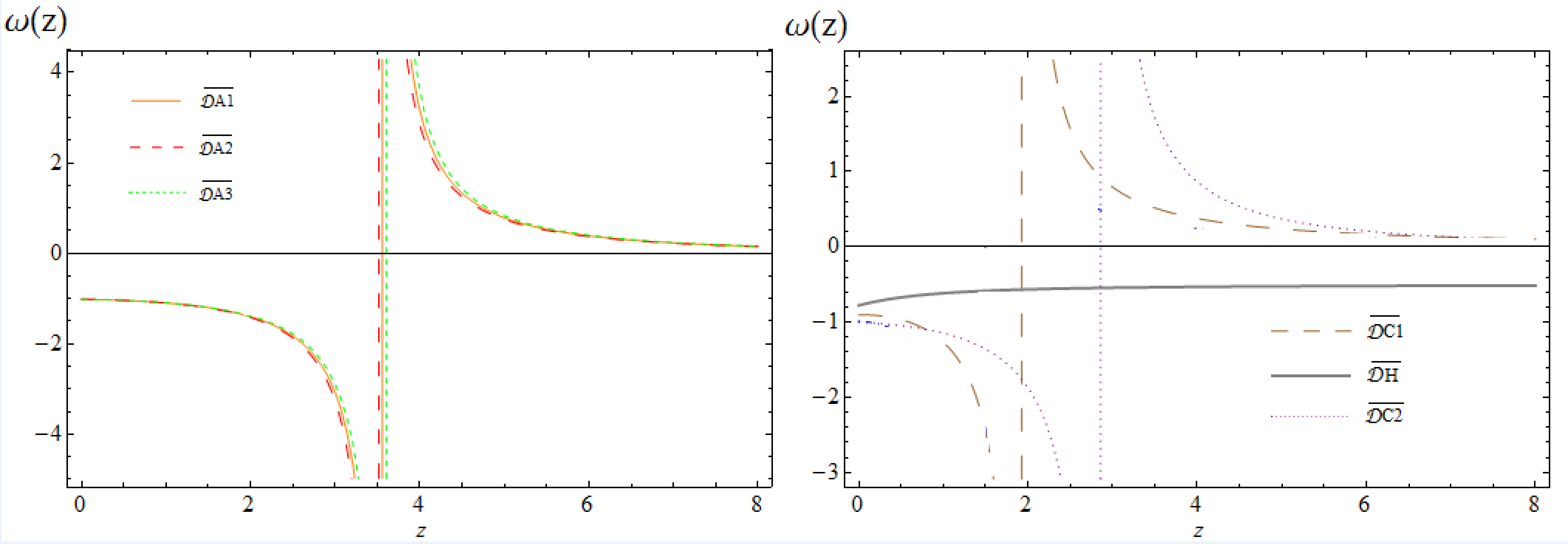
Large deviations with respect the LCDM value!

EoS parameter

$$\omega_D(z) = -1 + \frac{1+z}{3\rho_D(z)}\frac{d\rho_D(z)}{dz}$$



- The asymptotes are due to the vanishing of the DE density
- Near our time, the DA models exhibit a phantom behavior

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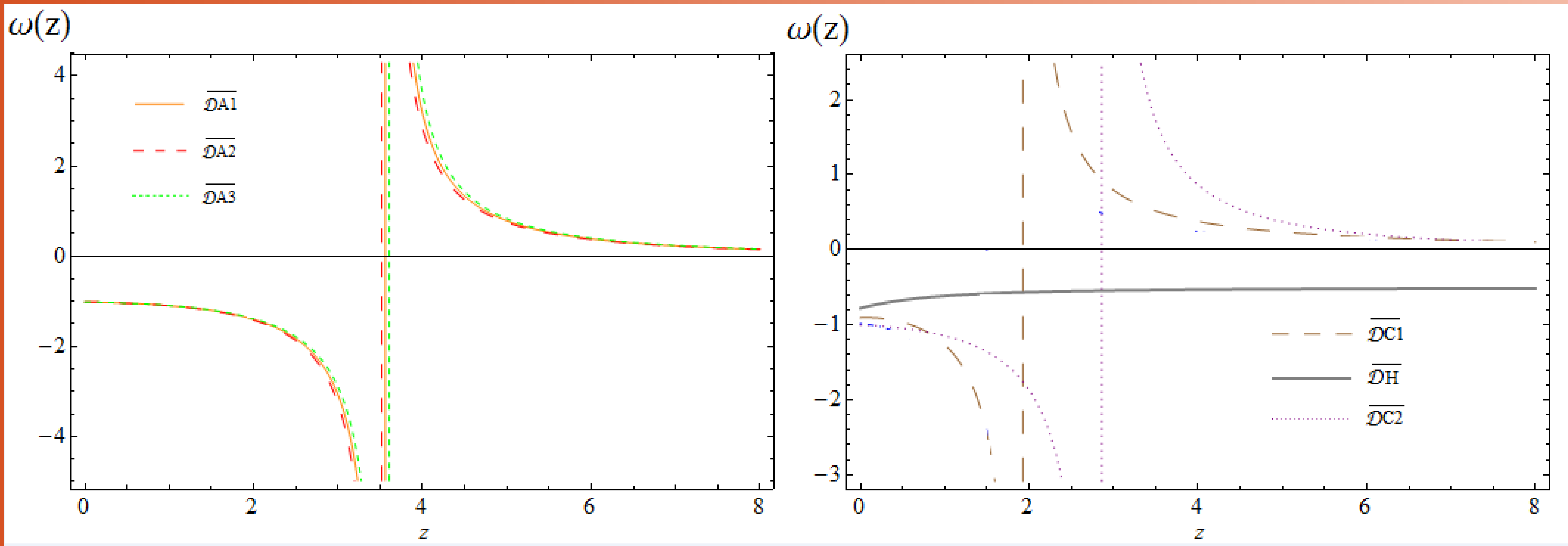

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The sign of ν_{eff} fixes the behavior of the DE fluid (phantom $\nu_{eff}<0$ or quintessence $\nu_{eff}>0$)

Linear structure formation

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- Differential equation that governs the growth of matter density perturbations

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- Assuming cold matter and DE self-conservation

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$$ds^2 = dt^2 + (-a^2\delta_{ij} + h_{ij})d\mathbf{x}^2$$

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$$\rho_m\left(\theta_m - \frac{\hat{h}}{2}\right) + 3H\delta\rho_m + \delta\dot{\rho}_m = 0$$

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$$\rho_m(\dot{\theta}_m + 5H\theta_m) + \theta_m\dot{\rho}_m = 0$$

$$\left\{\rho_D(1+\omega_D)(\dot{\theta}_D + 5H\theta_D) + \theta_D\left[\dot{\rho}_D(1+\omega_D) + \rho_D\dot{\omega}_D\right]\right\}\frac{a^2}{k^2} - (\omega_D\delta\rho_D + \rho_D\delta\omega_D) = 0$$

$$\theta_N \equiv \nabla_\mu \delta U^\mu_N$$

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5 equations and 6 unkowns!

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at sub-horizon scales, i.e. $\lambda << H^{-1}$

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Matter density contrast

$\delta_m \equiv \delta\rho_m / \rho_m$

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In terms of scale factor

$$\delta_m''' + \delta_m''\left(\frac{8}{a} + \frac{3H'}{H}\right) + \delta_m'\left(\frac{12}{a^2} + \frac{12H'}{aH} + \frac{H'^2}{H^2} + \frac{H''}{H}\right) = 0$$

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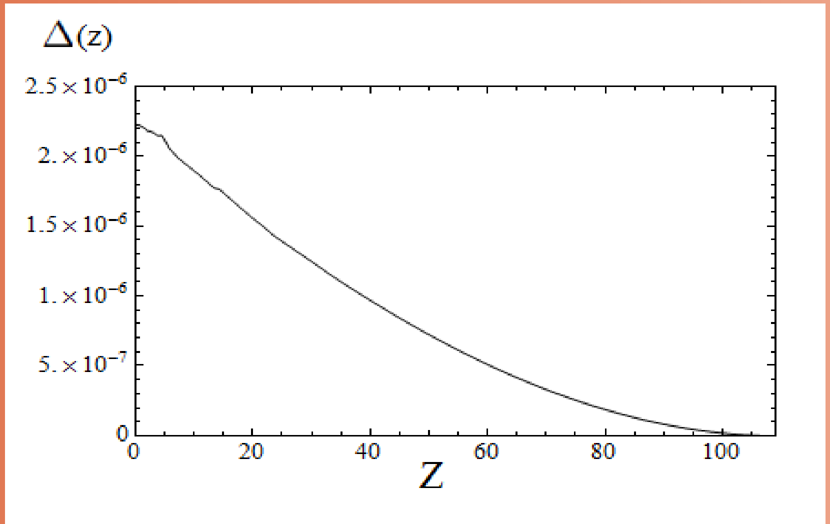

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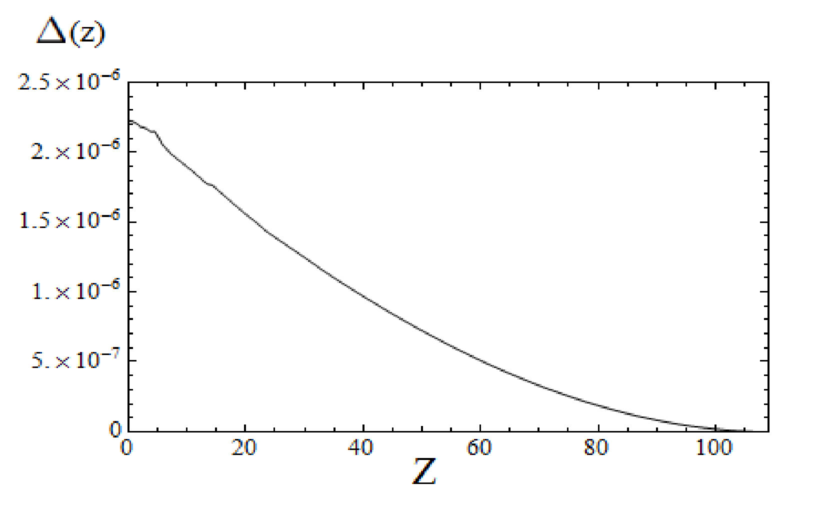
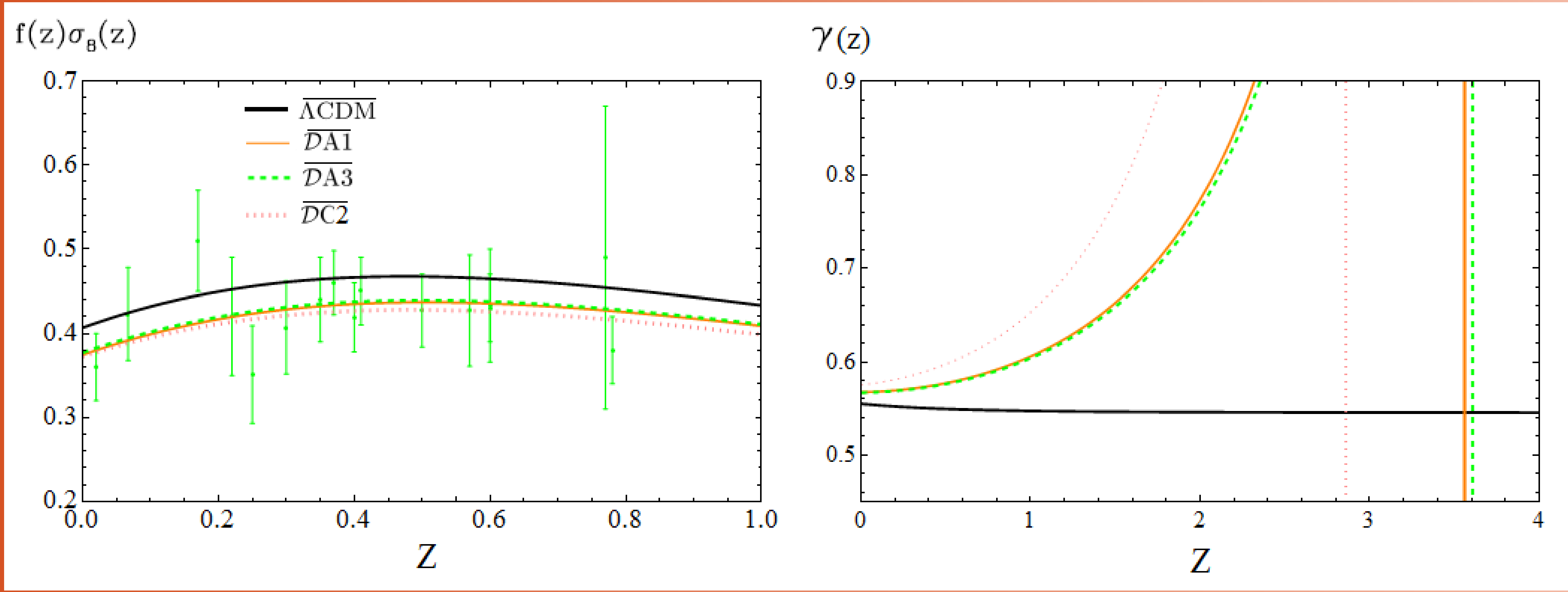


The corrections are really small!

Linear structure formation "observables"



Growth rate

$$f(z) = -(1+z)\frac{d\ln\delta_m}{dz}$$

Growth index

$$\gamma(z) \cong \frac{\ln\, f(z)}{\ln\, \Omega_m(z)}$$

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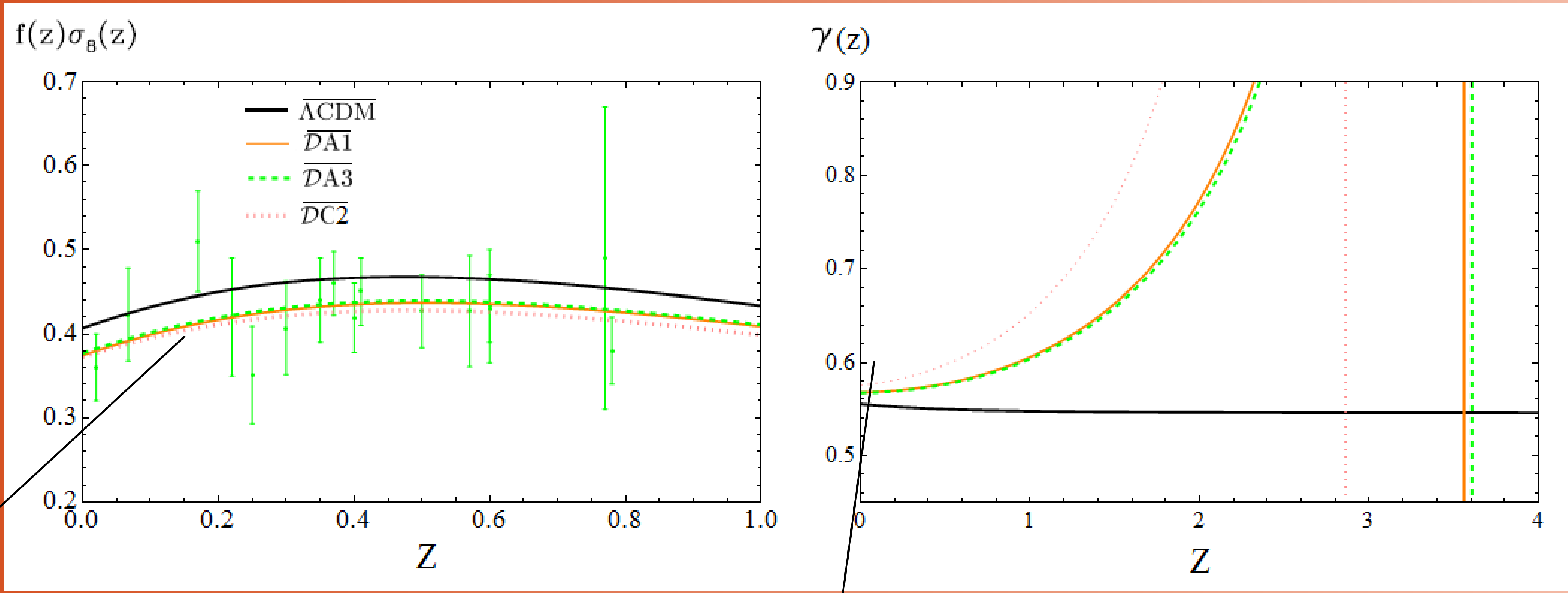


DA models fit better the data

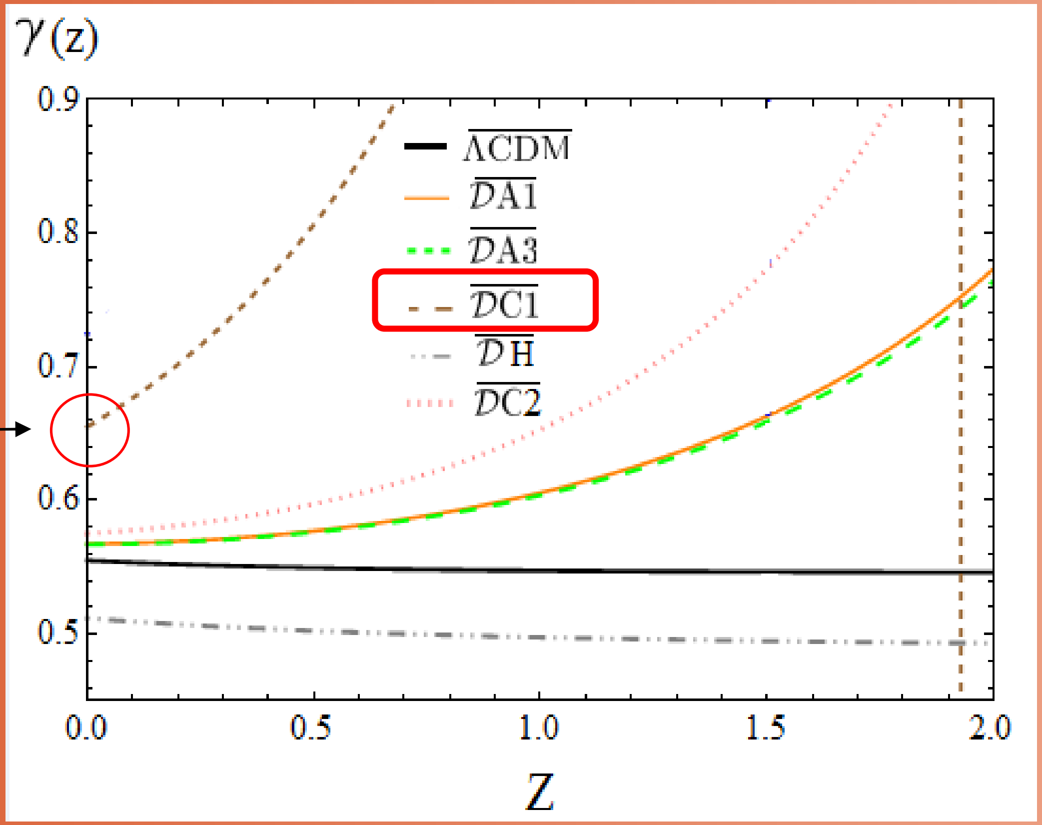
$$f(z) = -(1+z)\frac{d\ln\delta_m}{dz}$$

They respect the bound
$\gamma(0) = 0.56 \pm 0.05$

$$\gamma(z) \simeq \frac{\ln f(z)}{\ln \Omega_m(z)}$$

Linear structure formation "observables"

Big departure from the expected value



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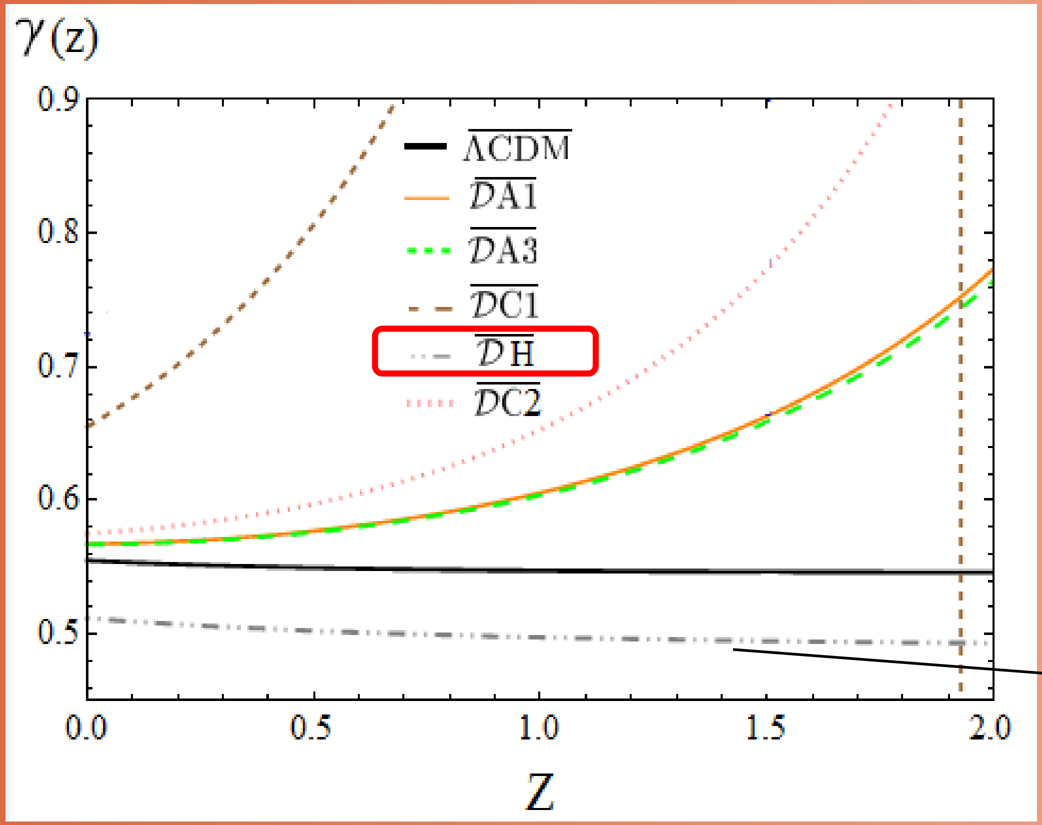

DH models cannot fit well at the same time the background and the structure formation data

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6. They could also explain the current phantom/quintessence-like behavior of the DE.

Thank you very much for your attention

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